

**Evidence of N₂-Ice On the Surface of
the Icy Dwarf Planet 136472 (2005 FY9)**

S. C. Tegler¹

Dept. Physics & Astronomy, Northern Arizona Univ, Flagstaff, AZ 86011

E-mail: Stephen.Tegler@nau.edu

W. M. Grundy¹

Lowell Observatory, 1400 W. Mars Hill Rd., Flagstaff, AZ 86001

E-mail: W.Grundy@lowell.edu

F. Vilas¹

MMT Observatory, PO Box 210065, University of Arizona, Tucson, AZ, 85721

Email: fvilas@mmto.org

W. Romanishin¹

Dept. Physics & Astronomy, Univ of Oklahoma, Norman, OK 73019

E-mail: wjr@nhn.ou.edu

D. Cornelison

Dept. Physics & Astronomy, Northern Arizona Univ, Flagstaff, AZ 86011

E-mail: David.Cornelison@nau.edu

G. J. Consolmagno¹, S.J

Vatican Observatory, Specola, Vaticana, V-00120, Vatican City State

Email: gjc@specola.va

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¹ Observer at the MMT Observatory. Observations reported here were obtained at the MMT Observatory, a joint facility of the University of Arizona and the Smithsonian Institution.

Proposed Running Head: N₂-Ice On 2005 FY9

Editorial Correspondence to:

Dr. Stephen C. Tegler

Dept Physics & Astronomy

Northern Arizona University

Flagstaff, AZ 86011

Phone: 928-523-9382

FAX: 928-523-1371

E-mail: Stephen.Tegler@nau.edu

Abstract

We present high signal precision optical reflectance spectra of 2005 FY9 taken with the Red Channel Spectrograph and the 6.5-m MMT telescope on 2006 March 4 UT (5000–9500 Å; 6.33 Å pixel⁻¹) and 2007 February 12 UT (6600–8500 Å; 1.93 Å pixel⁻¹). From cross correlation experiments between the 2006 March 4 spectrum and a pure CH₄-ice Hapke model, we find the CH₄-ice bands in the MMT spectrum are blueshifted by 3 ± 4 Å relative to bands in the pure CH₄-ice Hapke spectrum. The higher resolution MMT spectrum of 2007 February 12 UT enabled us to measure shifts of individual CH₄-ice bands. We find the 7296 Å, 7862 Å, and 7993 Å CH₄-ice bands are blueshifted by 4 ± 2 Å, 4 ± 4 Å, and 6 ± 5 Å. From four measurements we report here and one of our previously published measurements, we find the CH₄-ice bands are shifted by 4 ± 1 Å. This small shift is important because it suggests the presence of another ice component on the surface of 2005 FY9. Laboratory experiments show that CH₄-ice bands in spectra of CH₄ mixed with other ices are blueshifted relative to bands in spectra of pure CH₄-ice. A likely candidate for the other component is N₂-ice because its weak 2.15 μm band and blueshifted CH₄ bands are seen in spectra of Triton and Pluto. Assuming the shift is due to the presence of N₂, spectra taken on two consecutive nights show no difference in CH₄/N₂. In addition, we find no measureable difference in CH₄/N₂ at different depths into the surface of 2005 FY9.

Key Words: Kuiper Belt Objects, Spectroscopy, Trans-Neptunian Objects

1. Introduction

For more than 60 years, Pluto was the only known icy dwarf planet in the outer Solar System. The recent discovery of several more of them opens the door to comparative planetology studies of these small icy planets.

Pluto, Eris, and (136472) 2005 FY9 form a natural class for comparative studies, since the near-infrared spectra of all three are dominated by strong methane ice absorption bands (Owen et al. 1993; Brown et al. 2005; Licandro et al. 2006a). The existence of CH₄-ice on their surfaces, despite its relatively short life expectancy against photolysis and radiolysis, suggests that these objects experience similar surface and atmospheric activity. To this sample of objects with CH₄-ice and apparently young surfaces, we can add Neptune’s satellite Triton (likely to have had similar origins prior to its capture by Neptune) and perhaps Sedna (e.g., Barucci et al. 2005).

In addition to CH₄-ice absorptions, the 2.15 μ m band of nitrogen ice has also been reported on some of these objects (e.g., Cruikshank et al. 1993; Owen et al. 1993; Barucci et al. 2005). Since the N₂ absorption is intrinsically much weaker than the CH₄-ice absorptions, its detection requires abundant N₂-ice. N₂-ice is far more volatile than CH₄-ice. So where N₂-ice exists, it can be expected to dominate vapor pressure supported atmospheric compositions relative to CH₄. Much more N₂ than CH₄ can be sublimated, transported, and condensed on seasonal time scales (e.g., Spencer et al., 1997). That the more volatile N₂ ice does not simply bury the less mobile CH₄-ice hints at a complicated interplay between these two ices, which are miscible within one another (Prokhvatilov

and Yantsevich 1983).

Laboratory studies by Quirico and Schmitt (1997) showed that the wavelengths of near-infrared CH₄ ice absorption bands shift to shorter wavelengths when the CH₄ is diluted within N₂ ice. For ice mixtures with $0.1\% < \text{CH}_4 < 2\%$ they reported blueshifts of $\sim 0.006 \mu\text{m}$ (60 Å) relative to bands in pure CH₄-ice. The wavelengths of Triton’s CH₄ bands, blueshifted by $\sim 0.007 \mu\text{m}$ (70 Å), are consistent with its CH₄ being highly diluted in N₂ ice (Quirico et al. 1999). Pluto’s CH₄ wavelength shifts are smaller, suggesting that Pluto’s CH₄ occurs in a mixture of both diluted and undiluted phases (Douté et al. 1999; Grundy and Buie, 2001). Barucci et al. (2005) cross-correlation experiments between spectra of Sedna and Triton suggest Sedna’s CH₄-ice bands have a blueshift similar to Triton’s CH₄-ice bands. Licandro et al. (2006b) found blueshifts of 0 Å and 16 Å for the 7296 Å and 8897 Å bands in spectra of Eris. They suggest the different shifts reflect a decrease in the N₂ concentration as a function of depth into the surface of Eris.

If blueshifts of CH₄-ice bands correlate with the amount of N₂-ice, 2005 FY9 may have a surface richer in CH₄-ice. Licandro et al. (2006a) measured blueshifts of only 0 - 6 Å for CH₄ bands at optical wavelengths (see their Table 1), but questioned the reality of these shifts because they were so small. Our group independently measured blueshifts of 3 ± 2 Å for the same bands, thereby bolstering the case for the reality of the small shifts (Tegler et al. 2007). We note a possible typo in the wavelength of the $3\nu_1 + 4\nu_4$ band for pure CH₄-ice in Table 1 of Licandro et al., we think it should read 7296 Å rather than 7299

Å, and if so they see no shift for this band.

Recent laboratory measurements confirm a correlation between blueshifts of CH₄ bands and the amount of N₂-ice, even at much lower concentrations of N₂ than had previously been investigated. Cornelison et al. (2007) found that a CH₄ concentration of 98 % (i.e., a N₂ concentration of 2%) exhibited a small, but measureable, blueshift of 0.0002 μm (2 Å) in the $\nu_1 + \nu_4$ and $\nu_3 + \nu_4$ CH₄-ice bands at 2.3789 μm and 2.3234 μm . As the N₂ abundance increased, both bands exhibited progressively larger blueshifts. For comparison, Quirico and Schmitt (1997) found that samples with $0.1\% \leq \text{CH}_4 \leq 2\%$ exhibited blueshifts of 63 Å, 53 Å, and 26 Å for the $\nu_1 + \nu_4$ band, the $\nu_3 + \nu_4$ band, and the $2\nu_1 + \nu_3 + 2\nu_4$ band at 8897 Å.

Near-infrared spectra of 2005 FY9 are consistent with it having a CH₄-ice rich surface with trace amounts of N₂-ice. Brown et al. (2007) found unusually long optical path lengths through CH₄-ice, ~ 1 cm, compared to 100 μm for Pluto. In addition, they found no evidence of the N₂-ice band at 2.15 μm . Finally, Eluszkiewicz et al. (2007) used a microphysical and radiative transfer model to show that it is very unlikely to have long optical path lengths in both CH₄-ice and N₂-ice simultaneously on the same object.

The surfaces of Triton, Pluto, Eris, Sedna, and 2005 FY9 appear to exhibit a range of N₂/CH₄ mixing ratios, with 2005 FY9 possibly being the richest in CH₄-ice of the group. It is not yet clear why 2005 FY9 should be more CH₄-rich than the others, but this characteristic makes it an especially important target for comparative planetology studies.

Here we report new observations of 2005 FY9 that we combine with our previously published observation to arrive at a statistically significant blueshift of the CH₄ bands in the spectrum of 2005 FY9. In addition, we examine individual CH₄ bands of 2005 FY9 for differing shifts as seen in the spectra of Eris, and hence possible differences in CH₄/N₂ as a function of depth. We find no measureable difference in CH₄/N₂ as a function of depth.

2. Observations

We obtained spectra of 2005 FY9 on 2006 March 4 UT and 2007 February 12 UT with the 6.5-meter MMT telescope on Mt. Hopkins, AZ and the Red Channel Spectrograph. On 2006 March 4, we used a 150 g mm⁻¹ grating and a 1 × 180 arc sec slit that provided wavelength coverage of 5000–9500 Å in first order, a dispersion of 6.33 Å pixel⁻¹, and a FWHM resolution of 20.0 Å. On 2007 February 12, we used a 600 g mm⁻¹ grating and a 1 × 180 arc sec slit that provided wavelength coverage of 6600–8500 Å in first order, a dispersion of 1.93 Å pixel⁻¹, and a FWHM resolution of 4.7 Å. In Table 1, we present the UT dates, UT times, airmass values, exposure times, and gratings of our observations. Table 1 includes our previously published observations of 2005 FY9 on 2006 March 5 UT (Tegler et al., 2007).

There were high, thin cirrus clouds and the seeing was ~ 0.9 arc sec on both nights. 2005 FY9 was placed at the center of the slit and tracked at its rate.

We used the Image Reduction and Analysis Facility (IRAF) and standard procedures (Massey et al. 1992) to calibrate and extract one-dimensional spectra from the two-dimensional spectral images. Specifically, the electronic bias of

each image was removed by subtracting its overscan as well as a bias picture. Pixel to pixel sensitivity variations were removed from each image by dividing by a normalized twilight flatfield image. Extraction of one-dimensional spectra from the images was done with the `apall` task in IRAF. HeNeAr spectra taken before and after each set of object spectra were used to minimize the effects of flexure and obtain an accurate wavelength calibration. Measurements of airglow lines in the spectra indicate our wavelength scales are accurate to \sim one-tenth of a pixel or ~ 0.6 Å for the 2006 March 4 observations and 0.2 Å for the 2007 February 12 observations. We removed telluric bands and Fraunhofer lines from the 2005 FY9 spectra by observing the solar analog star HD 112257 (Hardorp, 1982) at airmasses very close to 2005 FY9, and then dividing the 2005 FY9 spectra by the normalized solar analog spectra. Typically, the airmass difference between 2005 FY9 and the solar analog star was ≤ 0.05 .

3. Results

3.1 Lower Resolution Spectrum of 2006 March 4 UT

First, we compare our spectrum of 2006 March 4 UT to our previously published spectrum of 2006 March 5 UT. In Figure 1, we plot the March 4 UT spectrum, a median of six 15-minute spectra corresponding to a total exposure time of 90 minutes (black line), and the published March 5 UT spectrum (Tegler et al., 2007), a median of four 10-minute exposures corresponding to a total exposure time of 40 minutes (red line). We combined the images by a median because the new deep depletion CCD is sensitive to cosmic rays. We assume an

albedo of 0.8 at 6500 Å for both spectra. Such a value is consistent with the albedo of 2005 FY9 measured with the Spitzer Space Telescope (Stansberry et al. 2007). We see no significant difference between the two spectra other than the March 4 spectrum has better signal precision than the March 5 spectrum. There are no period of rotation or obliquity measurements for 2005 FY9, and so the difference in rotational phase between the two nights is unknown. Furthermore, it is possible that 2005 FY9 has a nearly pole-on aspect.

Next, we compare our spectrum of 2006 March 4 UT to a spectrum of pure CH₄-ice. Such a comparison is important for three reasons. First, it demonstrates that the absorption bands in the spectrum of 2005 FY9 are due to CH₄-ice. Second, it demonstrates that the signal precision of our MMT spectrum rivals the signal precision of laboratory data. Finally, the comparison makes it possible for us to perform cross correlation experiments, and thereby measure the blueshifts of CH₄-ice bands in spectra of 2005 FY9.

We used Hapke theory (Hapke 1981, Hapke 1993) to transform laboratory optical constants of pure CH₄-ice at 30 K (Grundy et al. 2002) into an albedo spectrum for comparison to the MMT spectra. Specifically, we fit the MMT spectra of 2006 March 4 and March 5 UT with Hapke parameters of $h = 0.1$, $B_o = 0.8$, $\bar{\theta} = 30^\circ$, $P(g) =$ a two component Henyey-Greenstein function with 80% in the forward scattering lobe and 20 % in the back scattering lobe and both lobes having asymmetry parameter 0.63, and two grain sizes, 6 μ m (97% by volume) and 1 mm (3% by volume). These parameters are comparable to parameters in Hapke model fits of Pluto, Triton, and other outer Solar System

object spectra (e.g. see Grundy and Buie, 2001). We point out that the parameters do not represent a unique fit to the MMT spectra; however, they are plausible values for transparent, pure CH₄-ice grains. In Figure 2, we plot our 2006 March 4 UT spectrum (black line) and pure CH₄-ice Hapke model spectrum (red line). The comparison between this Hapke model and the published 2006 March 5 UT spectrum is given in Tegler et al. (2007). We emphasize that our goal here is to use the pure CH₄ Hapke model spectrum as a fiducial for blueshift measurements, not to arrive at unique values for Hapke parameters, and therefore say we know something definitive about the surface texture of 2005 FY9.

A visual inspection of the two spectra in Figure 2 clearly shows the absorption bands in the spectrum of 2005 FY9 are due to CH₄-ice. Furthermore, it appears the CH₄-ice bands in the MMT spectrum are slightly blueshifted relative to the bands of the pure CH₄-ice Hapke spectrum.

In order to quantify the apparent shift, we performed a cross-correlation experiment on the two spectra in Figure 2. In particular, we shifted the model spectrum from -12.66 Å to + 18.99 Å in 6.33 Å (i.e. 1 pixel) steps. For each shift, we calculated

$$\chi^2 = \frac{1}{N} \sum_i^N \frac{(y_{d,i} - y_{m,i})^2}{y_{m,i}} \quad (1)$$

where $y_{d,i}$ and $y_{m,i}$ represent the number of photons in wavelength bin i of the 2005 FY9 and Hapke spectra. In Figure 3, we present a plot of χ^2 vs. shift. The red curve is the best fit parabola to the calculated points. We find the parabola

has a minimum at a shift of 3 Å.

What is the uncertainty in the 3 Å measurement? We note that the HeNeAr spectra enabled us to calibrate the wavelengths in the 2005 FY9 spectrum to an uncertainty of $\sim 1/10$ of a pixel or ~ 0.6 Å. A larger source of uncertainty comes from the noise in the spectrum and the broadness of the cross correlation parabola in Figure 3. We applied the minimum χ^2 method to arrive at the 1σ confidence region (Avni, 1976). In short, we find the CH₄-ice bands in our 2006 March 4 spectrum of 2005 FY9 are blueshifted relative to the pure CH₄ Hapke model spectrum by 3 ± 4 Å, a result consistent with the blueshift in our 2006 March 5 UT spectrum, 3 ± 2 Å (Tegler et al., 2007).

3.2 Higher Resolution Spectrum of 2007 February 12 UT

Next, we compare our higher resolution MMT spectrum of 2007 February 12 UT to a pure CH₄-ice Hapke model. In Figure 4, we plot the MMT spectrum, a median of ten 10-minute spectra corresponding to a total exposure time of 100 minutes (black line), and a pure CH₄-ice Hapke model that is nearly identical to the Hapke model in Figure 2 (red line). In particular, the model here again uses laboratory optical constants for pure CH₄-ice at 30 K (Grundy et al., 2002), Hapke parameters $h = 0.1$, $B_o = 0.8$, $\bar{\theta} = 30^\circ$, and a two component Henyey-Greenstein function with 80% in the forward scattering lobe and 20% in the back scattering lobe and both lobes having asymmetry parameter 0.63. We again use grain sizes of 6 cm and 1 mm; however, here we use slightly different percentages by volume for the two grain sizes. Specifically, we use 98.3% and 1.7% instead of 97% and 3%. The major difference between the two models is

the model here gives slightly larger band depths than the model in section 3.1. In the top, middle, and bottom panels of Figure 4, we plot the 7296 Å, 7862 Å, and 7993 Å CH₄-ice bands. Considering there is no reason to expect the Hapke parameters to be constants in time or over the surface of 2005 FY9, it is remarkable that spectra of 2005 FY9 taken nearly a year apart can be fit by Hapke models with nearly identical parameters.

Again, visual inspection of Figure 4 suggests the CH₄ bands in the MMT spectrum are blueshifted relative to the pure CH₄ Hapke model. Because of the higher spectral resolution, this time we performed cross correlation experiments on individual bands. We plot the results of the cross correlation experiments in Figure 5. After applying the minimum χ^2 method, we found the 7296 Å, 7862 Å, and 7993 Å CH₄ bands in the MMT spectrum are blueshifted by 4 ± 2 Å, 4 ± 4 Å, and 6 ± 5 Å relative to the pure CH₄ Hapke model.

In order to test the sensitivity of our cross-correlation results to small changes in Hapke parameters (specifically the two different models in Figures 2 and 4), we performed a cross-correlation experiment between the two model spectra over the 7002 Å to 8505 Å wavelength range. In Figure 6, we plot χ^2 vs. shift. We find a minimum at 0 ± 4 Å, i.e. we find no measureable shift between the two pure CH₄ model spectra. It appears the slight difference in the model parameters has no systematic effect on the shifts.

In Table 2, we present a summary of our cross-correlation measurements. Five independent measurements all indicate the CH₄ bands in the spectra of 2005 FY9 are blueshifted relative to CH₄ bands in spectra of pure CH₄. The

average and standard deviation of the five measurements in Table 1 are 4 ± 1 Å, i.e. we find a 4σ detection of a shift. We interpret the shift as evidence of trace amounts of N₂-ice on the surface of 2005 FY9.

4. Discussion

In this section, we describe how our observations constrain the CH₄/N₂ abundance as a function of depth into the surface of 2005 FY9. Then, we compare our results to Eris (Licandro et al., 2006b). Finally, we put forth a possible mechanism to explain the differences between 2005 FY9 and Eris.

The average penetration depth of a photon at some wavelength depends on the reciprocal of the absorption coefficient, i.e. larger absorption coefficients absorb more light, preventing it from penetrating as deeply into the surface. Penetration depth also depends on scattering, which is a complex function of particle sizes, shapes, and spacing in a particular material, or of void shapes, sizes, and spacing in a compacted slab as envisioned by Eluszkiewicz et al. (2007). Photons which go on to be scattered out of a surface (and potentially be observed) sample shallower depths on average than the mean penetration depths, reducing the dependence of mean depth sampled on absorption coefficient. Nevertheless, weaker absorption bands do sample, on average, deeper surface strata.

Radiative transfer models can be used to get an idea of the depths sampled by the spectral observations. As described previously (Tegler et al., 2007), a Hapke model (Hapke 1993) with a bimodal particle size distribution can match the observed spectrum of 2005 FY9 reasonably well. We used 6 cm and 1 mm CH₄

ice particles, with mixing ratio 98.3% to 1.7% by volume. To match the spectral continuum, an artificial tholin-like absorber was dispersed within the CH₄ ice particles. These model parameters should not be taken as a unique solution for the surface texture of 2005 FY9, but rather as plausible values, consistent with the observed spectra, for purposes of investigating how deeply within the surface various wavelengths probe. These model parameters were used in a multiple scattering Monte Carlo ray tracing model (Grundy and Stansberry, 2000) to explore the trajectories followed by observable photons of different wavelengths. The average depths sampled are shown as a function of wavelength in Figure 7. The depths probed are highly sensitive to the assumptions made about void space (we assumed a 50% filling factor, but this value is merely conjectural – Eluszkiewicz et al’s compacted slab would have a filling factor closer to 100%) as well as particle (or void) shape, but the general results that the 7862 Å and 7993 Å absorption bands probe some 30 to 60% deeper than the 7296 Å band, and a factor of 2 to 3 times deeper than the much stronger 8897 Å band appear to be relatively robust.

Since we find no measurable difference in the blueshifts of the 7296 Å, 7862 Å, and 7993 Å bands of 2005 FY9 (see Figures 4 and 5), we find no measurable difference in the CH₄/N₂ ice abundance at the average depths probed by these bands (see Figure 7).

It appears that there is an important difference between the surfaces of 2005 FY9 and Eris. Licandro et al. (2006b) found the 7296 Å and 8897 Å bands of Eris were blueshifted by 0 ± 3 Å and 15 ± 3 Å, respectively, suggesting an

increase in the CH_4/N_2 abundance with depth below the surface of Eris. For 2005 FY9, we find no difference in the blueshifts of the 7296 Å, 7862 Å, and 7993 Å bands, suggesting a more uniform CH_4/N_2 abundance with depth. We note that if the 8897 Å band was blueshifted by 15 Å, we would have detected it in our low resolution spectra of 2005 FY9. Unfortunately, we were clouded out on the second night of our higher spectral resolution (2007 February) run, and therefore could not measure a separate blueshift for the 8897 Å band. On the other hand, the similar shifts of the 7296 Å bands of Eris and 2005 FY9 suggest similar CH_4/N_2 abundances below the depth sampled by the 8897 Å band.

What could account for the apparent depth-dependence of CH_4/N_2 abundance on Eris and absence thereof on 2005 FY9? Both bodies are currently near aphelion, so the surfaces of both might be expected to be characteristic of similar phases of their seasonal cycles, with the most volatile species having condensed last as both objects moved away from perihelion, as proposed for Eris by Licandro et al. (2006b). The obliquities of Eris and 2005 FY9 are not yet known. One possible difference could arise from their orientations. An object oriented equator-on to the Sun at aphelion would also have had its low latitudes exposed to sunlight at perihelion, when seasonal volatile transport would have been most active. Sublimation coupled with solar gardening on such a body, as envisioned by Grundy and Stansberry (2000) could account for increasing concentration of CH_4 with depth, as is observed on Eris. Since solar illumination is absorbed, on average, at greater depths within a surface composed of CH_4 and N_2 ices than the depths from which thermal emission escapes, sublima-

tion would be expected to take place from the subsurface. CH_4 is less volatile than N_2 , so its concentration would tend to increase where sublimation acts. In contrast, if 2005 FY9 is currently nearly pole-on to the Sun at aphelion, the opposite pole would have been oriented toward the Sun at perihelion, and the pole we see now would have been the winter hemisphere at perihelion, making it a depositional environment rather than the erosional environment which would be expected for the equator-on orientation.

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References

- Avni, Y., 1976. Energy spectra of x-ray clusters of galaxies. *Astrophys. J.* 210, 642-646.
- Barucci, M. A., Cruikshank, D. P., Dotto, E., Merlin, F., Poulet, F., Dalle Ore, C., Fornasier, S., and de Bergh, C., 2005. Is Sedna another Triton? *Astron. Astrophys.* 439, L1-L4.
- Brown, M. E., Barkume, K. M., Blake, G. A., Schaller, E. L., Rabinowitz, D. L., Roe, H. G., and Trujillo, C. A., 2007. Methane and ethane on the bright Kuiper belt object 2005 FY9. *Astron. J.* 133, 284-289.
- Brown, M.E., Trujillo, C. A., and Rabinowitz D. L., 2005. Discovery of a planetary-sized object in the scattered Kuiper belt. *Astrophys. J.* 635, L97-L100.
- Cornelison, D., Tegler, S. C., Grundy, W., Crisp, A., Abernathy, M., 2007. Near-infrared spectroscopy of CH₄ and N₂ ice mixtures: implications for icy dwarf planets. *Icarus*, submitted.
- Cruikshank, D. P., Roush, T. L., Owen, T. C., Geballe, T. R., de Bergh, C., Schmitt, B., Brown, R. H., Bartholomew, M. J., 1993. Ices on the surface of Triton. *Science* 261, 742-745.
- Douté, S., Schmitt, B., Quirico, E., Owen, T.C., Cruikshank, D. P., de Bergh, C., Geballe, T.R., and Roush, T. L., 1999. Evidence for methane segregation at the surface of Pluto. *Icarus* 142, 421-444.

- Eluszkiewicz, J., Cady-Pereira, K., Brown, M. E., Stansberry, J. A., 2007. Interpretation of the near-ir spectra of the Kuiper belt object (136472) 2005 FY9. *J. Geophys. Res.* 112, E06003.
- Grundy, W. M., and Buie, M. W., 2001. Distribution and evolution of CH₄, N₂, and CO ices on Pluto's surface: 1995 to 1998. *Icarus* 153, 248-263.
- Grundy, W.M., and J.A. Stansberry 2000. Solar gardening and the seasonal evolution of nitrogen ice on Triton and Pluto. *Icarus* 148, 340-346.
- Grundy, W. M., Schmitt, B., Quirico, E., 2002. The temperature-dependent spectrum of methane ice I between 0.7 and 5 μ m and opportunities for near-infrared remote thermometry. *Icarus* 155, 486-496.
- Hapke, B., 1981. Bidirectional reflectance spectroscopy. 1. Theory. *J. Geophys. Res.* 86, 4571-4586.
- Hapke, B., 1993. *Theory of Reflectance and Emittance Spectroscopy*. Cambridge Univ. Press, New York.
- Hardorp, J., 1982. The sun among the stars. V - A second search for solar spectral analogs: The Hyades' distance. *Astron. Astrophys.* 105, 120-132.
- Licandro, J., Pinilla-Alonso, N., Pedani, M., Oliva, E., Tozzi, G. P., Grundy, W. M., 2006a. The methane ice rich surface of large TNO 2005 FY9: a Pluto-twin in the trans-neptunian belt? *Astron. Astrophys.* 445, L35-L38.

- Licandro, J., Grundy, W. M., Pinilla-Alonso, N., Leisy, P., 2006b. Visible spectroscopy of 2003 UB313: evidence for N₂ ice on the surface of the largest TNO? *Astron. Astrophys.* 458, L5-L8.
- Massey, P., Valdes, F., Barnes, J., 1992. A user's guide to reducing slit spectra with IRAF (Tucson: NOAO), <http://iraf.noao.edu/iraf/ftp/iraf/docs/spect.ps.Z>
- Owen, T. C., Roush, T. L., Cruikshank, D. P., Elliot, J. L., Young, L. A., de Bergh, C., Schmitt, B., Geballe, T. R., Brown, R. H., Bartholomew, M. J., 1993. Surface ices and the atmospheric composition of Pluto. *Science* 193, 745-748.
- Prokhvatilov, A. I., and Yantsevich, L. D., 1983. X-ray investigation of the equilibrium phase diagram of CH₄-N₂ solid mixtures. *Sov. J. Low Temp. Phys.* 9, 94-98.
- Quirico, E., and Schmitt, B., 1997. Near-infrared spectroscopy of simple hydrocarbons and carbon oxides diluted in solid N₂ and as pure ices: implications for Triton and Pluto. *Icarus* 127, 354-378.
- Quirico, E., Douté, S., Schmitt, B., de Bergh, C., Cruikshank, D. P., Owen, T. C., Geballe, T. R., and Roush, T. L., 1999. Composition, physical state, and distribution of ices at the surface of Triton. *Icarus* 139, 159-178.
- Spencer, J. R., Stansberry, J. A., Trafton, L. M., Young, E. F., Binzel, R. P., and Croft, S. K., 1997. Volatile transport, seasonal cycles, and atmospheric

dynamics on Pluto. In *Pluto and Charon* (S. A. Stern and D. J. Tholen, Eds), University of Arizona Press, Tucson, pp. 435-473.

Stansberry, J., Grundy, W., Brown, M., Cruikshank, D., Spencer, J., Trilling, D., and Margot, J., 2008. Physical properties of Kuiper belt and Centaur objects: constraints from Spitzer Space Telescope. In *The Solar System Beyond Neptune* (A. Barucci, H. Boehnhardt, D. Cruikshank, and A. Morbidelli, Eds.), Univ Arizona Press, Tucson, in press.

Tegler, S. C., Grundy, W. M., Romanishin, W., Consolmagno, G. J., Mogren, K., Vilas, F., 2007. Optical spectroscopy of the large Kuiper belt objects 136472 (2005 FY9) and 136108 (2003 EL61). *Astron. J.* 133, 526-530.

Table 1
Dates, Times, Gratings of 2005 FY9 Observations

UT Date	UT Time ^a (hh:mm)	Airmass ^a	Exp Time (min)	Grating (g/mm)
2006 Mar 04	06:56	1.11	900	150
	07:20	1.07	900	150
	07:47	1.04	900	150
	08:03	1.02	900	150
	08:28	1.01	900	150
	08:44	1.00	900	150
2006 Mar 05 ^b	05:08	1.49	600	150
	05:31	1.37	600	150
	06:05	1.24	600	150
	06:49	1.12	600	150
2007 Feb 12	10:01	1.00	600	600
	10:11	1.00	600	600
	10:27	1.00	600	600
	10:38	1.00	600	600
	11:19	1.02	600	600
	11:29	1.03	600	600
	11:39	1.05	600	600
	12:22	1.11	600	600
	12:32	1.13	600	600
	12:43	1.16	600	600

^a Values at beginning of exposures.

^b Tegler et al. (2007).

Table 2
Blueshifts of CH₄-Ice Bands

UT Date	Cross-Corr Range (Å)	Blueshift (Å)
2006 Mar 04	7020–9280	3 ± 4
2006 Mar 05 ^a	7020–9280	3 ± 2
2007 Feb 12	7150–7400	4 ± 2
	7800–7900	4 ± 4
	7920–8020	6 ± 5

^a Tegler et al. (2007).

Figure Captions

Fig. 1. Portions of our lower resolution albedo spectra of 2005 FY9 taken with the 6.5-m MMT telescope and the Red Channel Spectrograph on 2006 March 4 UT (black line) and 2006 March 5 UT (red line). Tick marks indicate maximum absorptions of pure CH₄-ice bands at 7296, 7862, 7993, 8415, 8442, 8691, 8897, 8968, and 9019 Å. We find no measureable difference between the CH₄-ice bands on two consecutive nights.

Fig. 2. Our MMT 2006 March 4 UT albedo spectrum of 2005 FY9 (black line) and a pure CH₄-ice Hapke model with grain sizes of 6 cm and 1 mm (red line). Tick marks indicate maximum absorptions of pure CH₄-ice bands. A visual inspection suggests the CH₄ bands in the MMT spectrum are slightly blueshifted relative to the bands in the pure CH₄-ice Hapke model.

Fig. 3. Results of cross-correlation experiments between the 2006 March 4 MMT spectrum of 2005 FY9 and the pure CH₄-ice Hapke model in Fig. 2. The χ^2 parabola reaches a minimum at a 3 ± 4 Å blueshift of the data relative to the model.

Fig. 4. Three portions of our higher resolution 2007 February 12 MMT spectrum of 2005 FY9 (black line) and a pure CH₄-ice Hapke spectrum with grain sizes of 6 cm and 1 mm (red line). Top, middle, and bottom panels show the 7296 Å, 7862 Å, and 7993 Å CH₄-ice bands. Tick marks indicate the wavelengths of maximum absorption by pure CH₄-ice. A visual inspection suggests

the three CH₄-ice bands in the MMT spectrum are slightly blueshifted relative to the bands in the pure CH₄-ice Hapke model.

Fig. 5. Results of cross-correlation experiments between our 2007 February 12 MMT and pure CH₄-ice Hapke spectra in Figure 4. The χ^2 parabolas for the 7296 Å (top panel), 7862 Å (middle panel), and 7993 Å (bottom panel) bands reach minima at 4 ± 2 Å, 4 ± 4 Å, and 6 ± 5 Å blueshifts of the data relative to the model.

Fig. 6. Results of cross-correlation experiments between two nearly identical pure CH₄-ice Hapke spectra in Figures 2 and 4. The parabola has a minimum at 0 ± 4 Å.

Fig. 7. Mean depth sampled by observable photons from 2005 FY9 as a function of wavelength, from a Monte Carlo ray-tracing model (red line). The depth sampled depends a number of poorly constrained factors, such as the porosity and the shapes of the particles. Higher porosity, or more forward scattering particles increase the mean depth sampled. The effect of a $\pm 5\%$ albedo uncertainty is indicated by the width of the gray zone. Considering how little is known at present, the depths here are representative, rather than definitive. The important things to note from this figure are the relative depths probed by various CH₄ ice absorption bands.













